MULTI-PURPOSE MULTI-FUNCTION SURFACE-TENSION MICROFLUIDIC MANIPULATOR

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

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FIELD OF THE INVENTION

The present invention relates to microfluidic devices capable of manipulating fluid analytes and reagents adsorbed onto the device surface. The device provides the basic microfluidic operations of transport, merge, subdivide, separate, sort, remove, and capture. These operations are made possible by controlling the generation and placement of localized thermal gradients that induce localized surface tension gradients in the fluids on the surface.

BACKGROUND OF THE INVENTION

The need for a cost-effective and flexible microfluidic device that can readily manipulate nano-liter and pico-liter amounts of fluids is increasingly important as many fields of science explore the nanometer regime. Popular methods for handling microfluids use a physical flow path such as micro-channels or hydrophilic/hydrophobic patterns. All physical paths have the drawback of a static channel network, limiting the fluid to a predefined route.

Often in microfluidic systems, flow actuation is accomplished by non-mechanical means such as dielectrophoretic forces and surface tension. In the presence of a surface tension gradient it is well known that fluids adsorbed onto a surface can be laterally transported. Adsorbed fluids move from a high temperature region to a lower temperature region. This surface-tension-driven fluid motion is called the Marangoni effect (1, 2).

A surface tension gradient can be produced by several approaches: chemical, composition, thermal, electrochemical, and photochemical. Chemical and composition gradients usually result in static surface tension heterogeneity. The latter three approaches lend the possibility of a dynamically applied surface tension gradient at one or more specified locations, of which thermal is the most versatile since it does not require special reactant chemicals. In addition, all analytes have characteristic thermophysical properties that will respond differently to a surface tension gradient, making possible the selective transport of analytes based on species. Since a thermal gradient causes a surface tension gradient, which in turn causes adsorbate motion, the terms thermal gradient and surface tension gradient will be used interchangeably. Also, the terms analyte, reagent, adsorbed mass, molecules adsorbed onto a surface, fluid adsorbed onto a surface, and fluid will be used interchangeably.

Our device utilizes a controllable array of micro-scale surface or sub-surface thermal elements that can be made to produce dynamic, micro-scale, overlapping surface tension gradients on demand. The result is the precise production and placement of locally confined surface tension gradients that make possible the basic microfluidic operations of transport, merge, subdivide, separate, sort, remove (desorb), and capture (adsorb).

Transport occurs when a thermal gradient is produced directly under the analyte, causing the analyte to move in one direction. Merging occurs when one or more fluids are transported to the same location, causing the analytes to collide into one adsorbate mass. Subdivision occurs when the source of heat, either a dot or line, is directly

underneath the analyte and a thermal gradient radiates in all directions from that source, causing the adsorbate mass to split into two or more smaller adsorbate masses. Separation occurs when a thermal gradient of a particular temperature distribution causes only one type of analyte to be transported. Sort occurs when separated analytes are ordered through transport. Removal occurs when the temperature of the surface directly under the analyte is above its vaporization point, causing the analyte to evaporate or sublimate off the surface. Capture occurs when the temperature of the surface is cooled, causing fluid to be adsorbed onto the surface.

This versatile microfluidic device has many applications, including "laboratories on a chip" (lab-on-a-chip) and pre-concentration. Lab-on-a-chip technologies offer disposable, fast, and inexpensive chemical experiments. By spatially controlling molecules adsorbed onto a surface, the device permits micro-scale studies of chemistry, biology, and physics. For example, fundamental studies in surface tension and interface phenomena can be explored with the operations of transport, merge, subdivide, separate, sort, remove, and capture. The device allows micro-chemical analysis of complex fluids. Analytes, cells, proteins, and DNA may be transported, separated, sorted, and merged. Micro-scale reactions may be executed by merging individual reactants in an ordered sequence.

Another application of this microfluidic device is a preconcentrator to increase detection sensitivity of analytical instruments such as gas chromatographs, chemiluminescence detectors or thermal energy analyzers, ion mobility spectrometers, mass spectrometers, micro-electro-mechanical-system (MEMS) sensors, and other sensor/detector devices. Most preconcentrators are cumbersome instruments that draw a large volume of air, collect organic compounds from the surroundings onto a chemical filter, and vaporize the organics into the analytical instrument. Our microfluidic device can perform the same function in an economical, compact manner.

A particularly valuable application of our invention is a preconcentrator to a MEMS sensor. Because of their small mass, MEMS-based sensors offer a number of unique and

distinct advantages. However for a MEMS sensor, a Faustian bargain exists between sensitivity and probability. For example, one type of MEMS sensor is the microcantilever (3), where single molecules adsorbed on the cantilever surface can be detected but whose surface area is only about 10^{-4} cm^2. The small surface area means that the probability of a particle interacting with the sensor area is extremely low, resulting in lower sensitivity for a given analyte concentration. However, a microfluidic manipulator adsorbing particles onto an area of about 1 cm^2, concentrating the particles to a smaller area, and delivering the particles to the microcantilever through vaporization, would effectively increase the probability of capturing a particle by a factor of 10^4. Prior to our invention, none of the currently available technologies have been able to offer a clear path to the development of such an extremely sensitive, hand held, MEMS-based sensor.

Thus, we provide a multipurpose microfluidic device that spatially controls adsorbed molecules on a surface by providing the basic microfluidic operations of transport, merge, subdivide, separate, sort, remove, and capture. Further and other aspects of the present invention will become apparent from the description contained herein.

REFERENCES

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2. N. Garnier, et. al., "Optical Manipulation of Microscale Fluid Flow", Phys. Rev. Lett., Vol. 91.054501, pp. 1-4 (2003).

3. U. S. Patent No. 5,719,324, issued February 17, 1998, "Microcantilever Sensor", T. G. Thundat, et. al.

SUMMARY OF THE INVENTION

In one embodiment, the invention is a microfluidic manipulator for an adsorbed fluid, comprising a material having a surface for adsorbing fluids, the material provided with a plurality of individually controllable thermal elements that produce thermal gradients on the surface that produce surface tension gradients at the interface between the adsorbed fluid and the surface sufficient to cause the adsorbed fluid to move on the surface; wherein one or more of the thermal elements are controlled to transport adsorbed fluids on the surface.

In another embodiment, the invention is a microfluidic manipulator for an adsorbed fluid, comprising a material having a surface for adsorbing fluids, the material provided with a plurality of individually controllable thermal elements that produce thermal gradients on the surface that produce surface tension gradients at the interface between the adsorbed fluid and the surface sufficient to cause the adsorbed fluid to move on the surface; wherein one or more of the thermal elements are controlled to merge adsorbed fluids on the surface.

In a further embodiment, the invention is a microfluidic manipulator for an adsorbed fluid, comprising a material having a surface for adsorbing fluids, the material provided with a plurality of individually controllable thermal elements that produce thermal gradients on the surface that produce surface tension gradients at the interface between the adsorbed fluid and the surface sufficient to cause the adsorbed fluid to move on the surface; wherein one or more of the thermal elements are controlled to subdivide adsorbed fluids on the surface.

In a still further embodiment, the invention is a microfluidic manipulator for an adsorbed fluid, comprising a material having a surface for adsorbing fluids, the material provided with a plurality of individually controllable thermal elements that produce thermal gradients on the surface that produce surface tension gradients at the interface between the adsorbed fluid and the surface sufficient to cause the adsorbed fluid to move

on the surface; wherein one or more of the thermal elements are controlled to separate adsorbed fluids on the surface.

In yet another embodiment, the invention is a microfluidic manipulator for an adsorbed fluid, comprising a material having a surface for adsorbing fluids, the material provided with a plurality of individually controllable thermal elements that produce thermal gradients on the surface that produce surface tension gradients at the interface between the adsorbed fluid and the surface sufficient to cause the adsorbed fluid to move on the surface; wherein one or more of the thermal elements are controlled to sort adsorbed fluids on the surface.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates an embodiment of the invention that features thermal elements in the form of non-intersecting lines.

FIG. 2 illustrates an embodiment of the invention that features thermal elements in the form of an X-Y orthogonal system of lines.

FIG. 3 illustrates an embodiment of the invention that features thermal elements in the form of non-intersecting closed lines.

FIG. 4 illustrates an embodiment of the inventionthat features thermal elements in the form of an R-θ system of orthogonal lines.

FIG. 5 illustrates an embodiment of the invention that features thermal elements in the form of a combination of patterned lines.

FIG. 6 illustrates an embodiment of the invention that features thermal elements and a micro-electro-mechanical-system (MEMS) sensor/detector.

FIG. 7 illustrates an embodiment of the invention that features collectively controlled thermal elements.

FIG. 8 illustrates an embodiment of the invention that features thermal elements in the form of an array of dots.

FIG. 9 illustrates an embodiment of the invention that features thermal elements in the form of a stochastic system of dots of various sizes.

FIG. 10 illustrates an embodiment of the invention that features thermal elements in the form of a combination of lines and dots.

FIGS. 11 and 12 illustrate the transport operation of the invention using the embodiment of FIG. 2.

FIGS. 13 and 14 illustrate the subdivide operation of the invention using the embodiment of FIG. 2.

FIGS. 15 and 16 illustrate the subdivide operation of the invention using the embodiment of FIG. 8.

FIGS. 17 and 18 illustrate the merge operation of the invention using the embodiment of FIG. 2.

FIGS. 19 through 21 illustrate the separate operation of the invention using the embodiment of FIG. 2.

FIGS. 22 and 23 illustrate the sort operation of the invention using the embodiment of FIG. 2.

FIGS. 24 through 26 illustrate the desorb operation of the invention using the embodiment of FIG. 8.

FIGS. 27 and 28 illustrate the adsorb operation of the invention using the embodiment of FIG. 8.

FIG. 29 illustrates the FIG. 2 embodiment of the invention in more detail, and also illustrates a control system that may be used with all the embodiments of the invention.

FIG. 30 illustrates the embodiment of FIG. 29 in further detail.

FIG. 31 illustrates the embodiment of FIG. 29 in still further detail.

FIG. 32 illustrates the transport operation of the embodiment of FIG. 29.

FIG. 33 also illustrates the transport operation of the embodiment of FIG. 29

DETAILED DESCRIPTION OF THE INVENTION

The microfluidic manipulator is illustrated in ten embodiments in FIGS. 1 - 10. In all of these embodiments, not drawn to scale, the microfluidic manipulator has a surface upon which the analyte vapors are allowed to adsorb. The manipulator is provided with individually controllable thermal elements that produce thermal gradients on the surface and control the temperature on the surface. The thermal elements may take the form of non-intersecting lines in FIG. 1, an X-Y orthogonal system of lines in FIG. 2, non-intersecting closed lines in FIG. 3, an R-θ system of orthogonal lines in FIG. 4, a combination of patterned lines in FIG. 5, a combination of thermal elements and a micro-electro-mechanical-system (MEMS) sensor/detector as in FIG. 6, collectively controlled thermal elements as in FIG. 7, an array of dots in FIG. 8, a stochastic system of dots of

various sizes as in FIG. 9, and a combination of line and dots as in FIG. 10. Fluids are adsorbed and desorbed at selected locations on the surface by controlling the localized surface temperature by the thermal elements. The adsorbed fluids are preferentially manipulated by localized thermal gradients caused by the thermal elements.

In the device embodiments shown in FIGS. 1-10 the microfluidic manipulators **100, 200, 300, 400, 500, 600, 700, 800, 900, 1000** with surfaces **101, 201, 301, 401, 501, 601, 701, 801, 901, 1001** for fluid adsorption may be fabricated from any suitable material that will electrically isolate and sufficiently thermally isolate the thermal elements **102, 202, 302, 402, 502, 503, 602, 702, 703, 802, 902, 1002, 1003**. The device can be fabricated from a semiconducting material such as silicon, gallium arsenide, germanium, etc. The device can also be fabricated from insulating materials such as mica, glass, silicon dioxide, silicon nitride, silicon carbide, sapphire, diamond, fused silica, fused quartz, etc. The device may be a polymer such as silicone rubber or polyimide. The material may be rigid or flexible.

The thermal elements **102, 202, 302, 402, 502, 503, 602, 702, 703, 802, 902, 1002, 1003** can be resistive heaters that heat the surface in order to produce a thermal gradient when electrical current is applied. The thermal elements **802, 902, 1002** can also be Peltier Effect junctions that heat or cool the surface in order to produce a thermal gradient, depending on the direction of the applied electrical current. The methods used to fabricate the thermal elements **102, 202, 302, 402, 502, 503, 602, 702, 703, 802, 902, 1002, 1003** include conducting thin films and ion implantation. Conducting or metal thin films may include gold, platinum, palladium, aluminum, nickel, copper, chrome, etc. Compound thin films may include hafnium diboride (HfB_2), titanium-tungsten nitride (TiWN), cobalt silicide ($CoSi_2$), titanium silicide ($TiSi_2$) or other silicides (molybdenum, tungsten, magnesium), etc.

In the embodiments of FIGS. 1 and 3, the thermal elements **102, 302** take the form of non-intersecting lines that produce thermal gradients in one direction on the surface **101, 301**. In FIG. 1, the thermal elements **102** extending in the Y direction will

produce thermal gradients in the X direction. Likewise in FIG. 3, the thermal elements **302** extending in the θ direction will produce thermal gradients in the r direction.

In the embodiments of FIGS. 2 and 4, the thermal lines **202, 402** are disposed orthogonally to be capable of producing thermal gradients in two directions. When a current is passed through individually selected lines **202, 402**, the result is two-dimensional control of the thermal gradient in either the X-Y or r-θ direction on the surface **201, 401**.

In the embodiment of FIG. 5, the thermal lines **502, 503** take the form of a combination of different line shapes, each operated for a particular fluid manipulation operation. For example, the curved thermal elements **503** can be individually controlled to transport adsorbed fluid onto the alternatingly patterned thermal element **502**, after which the thermal element **502** is heated to desorb the fluid off the surface **501**. This embodiment would be useful as a preconcentrator for a nearby detector device, for example.

In the embodiment of FIG. 6, the microfluidic manipulator **600** is integrated with a sensor/detector device. A MEMS sensor/detector in the form of a microcantilever **603** is attached to, or made integral with, the surface **601**. The thermal elements **602** are controlled in a manner to transport adsorbed fluids from the larger surface **601** onto the much smaller microcantilever **603**.

In the embodiment of FIG. 7, two or more thermal elements **702, 703** may be electrically connected to efficiently control the thermal gradient for a specific application. For example, the two sets of thermal lines **702, 703** may be operated consecutively for accelerated transport in the Y direction.

In the embodiments of FIGS. 8 and 9, the thermal elements **802, 902** take the form of dot heaters. These may be resistive heaters or Peltier Effect junctions capable of producing thermal gradients at a single spot on the surface **801, 901** by either heating or

cooling the surface. Each element **802, 902** produces a spatially localized thermal gradient on the surface **801, 901** radially direction from that element. The thermal elements **802, 902** in the form of dots can be individually controlled for the microfluidic manipulations of transport, merge, subdivide, separate, and sort. In addition, each thermal element **802, 902** controls the surface temperature at a specific location. Adsorbed fluid may be desorbed, that is, removed from a specific location by heating that location. If the thermal elements **802, 902** are Peltier Effect junctions, a greater adsorption will occur at a specific location on the surface **801, 901** by cooling that location.

In the embodiment of FIG. 10, the thermal elements **1002, 1003** take the form of dots **1002** and lines **1003**. The thermal dots **1002** may be Peltier Effect junctions that can both heat and cool while the thermal lines **1003** may be resistive heaters. FIG. 10 thus illustrates the use of both resistive heaters and Peltier Effect junctions.

All of the embodiments of the microfluidic manipulator shown in FIGS. 1-10 may be operated to transport, subdivide, merge, separate, sort, remove, and capture fluids adsorbed onto the surface.

The transporting of adsorbed fluids is illustrated in FIGS. 11 and 12. The device **1100** has a surface **1101** provided with a plurality of mutually orthogonal thermal elements **1102, 1103**. Adsorbed fluids **1104, 1105** are present on the surface **1101**. The heating elements **1102, 1103** are heated to produce thermal gradients in the Y and X directions, respectively. When the thermal element **1102** is heated, the adsorbed fluids **1104, 1105** are close enough to the thermal element **1102** to be affected by the surface tension gradient, and consequently move in the Y direction away from the higher temperature. This is shown in FIG. 12. Similarly, when the thermal element **1103** is heated, the adsorbed fluid **1105** moves in the X direction away from the higher temperature, also shown in FIG. 12. The adsorbed fluids **1104** are too far away from thermal element **1103**, and thus are not moved in the X direction by the surface tension gradient from the thermal element **1103**. It is readily seen that the thermal elements **1102, 1103** may be heated consecutively or simultaneously. Thus, by proper design and

control of the many thermal elements capable of producing the X and Y thermal gradients, it is possible to efficiently transport adsorbed fluids over the surface **1101**. In one example, the transport operation may move adsorbed fluids scattered over a large surface area to one localized area on the surface, thereby concentrating the adsorbed fluids. This embodiment of the invention, then, provides a novel chemical pre-concentrator that could be used, for example, as the front-end to an analytical instrument.

The subdividing of adsorbed fluids is illustrated in the two embodiments shown in FIGS. 13, 14 and 15, 16 respectively. In FIG. 13, the device **1200** has a surface **1201** provided with a plurality of mutually orthogonal thermal elements **1202** on which adsorbed fluids **1203** are present. The heating elements **1202** are heated to produce thermal gradients in the X and Y directions directly under the adsorbed fluid **1203**. As a result, the adsorbed fluid **1203** is subdivided into small volumes **1204** on the surface **1201**, as shown in FIG. 14.

In the other embodiment shown in FIGS. 15, 16, the device **1300** has a surface **1301** provided with a plurality of Peltier Effect heating elements **1302**, on which an adsorbed fluid (or fluids) **1303** is present. The Peltier junction **1302** located directly under the adsorbed fluid **1303** is heated to produce a thermal gradient that is radially directed. As a result, the adsorbed fluid **1303** is subdivided into a number of smaller volumes **1304** of varying sizes, as shown in FIG. 16.

The merging of adsorbed fluids is illustrated in FIGS. 17 and 18. The device **1400** has a surface **1401** provided with a plurality of X-direction and Y-direction thermal elements on which adsorbed fluids **1403** are present. The Y-direction heating elements **1402** are heated to produce thermal gradients in the X direction. As the adsorbed fluids **1403** move away from the regions of higher temperature produced by the thermal elements **1402**, the fluids merge to form a larger volume **1404** due to nucleation, as shown in FIG. 18. One application of this embodiment of the invention would be as a surface for merging several different adsorbed species in an ordered sequence for micro-scale reactions.

The separating of adsorbed fluids is illustrated in FIGS. 19, 20, and 21. The device **1500** has a surface **1501** provided with thermal elements **1502-1507**, on which adsorbed fluids 1508 are present. The adsorbed fluid **1508** is comprised of two dissimilar species **1509, 1510**. The thermal elements **1503** and **1506** located directly under the adsorbed fluid volume **1508** are heated to produce thermal gradients in the X and Y directions. As a result of the thermal gradients, the adsorbed fluid **1508** is subdivided into small volumes **1511** on the surface **1501**, as illustrated in FIG. 20. The thermal elements **1502, 1504, 1505, 1507** are then heated to produce thermal gradients in the X and Y directions which further subdivide and separate the fluid into smaller volumes of like species, illustrated at **1509, 1510** in FIG. 21. The separation occurs because different species have different surface tension, mass, and mobility, thus the different species will be transported different distances under the influence of the same thermal gradient. This embodiment of the invention can be the basis for a novel way of obtaining chemical selectivity.

The sorting of absorbed fluids is illustrated in FIGS. 22 and 23. The device **1600** has a surface **1601** provided with thermal elements **1602**, on which two dissimilar adsorbed fluids **1603, 1604** are present. The thermal elements **1602** are heated to produce thermal gradients in the Y direction. Because different species have different surface tension, mass, and mobility, they will be transported different distances under the influence of the same thermal gradient. As a result, the two species **1603, 1604** may be sorted to different locations on the surface **1601**, as illustrated in FIG. 23.

The removal, or desorption, of absorbed fluids is illustrated in FIGS. 24, 25, and 26. The device **1700** has a surface **1701** provided with a plurality of Peltier Effect junctions **1702**, on which two dissimilar adsorbed fluids **1703, 1704** are present. The Peltier heating elements **1702** are heated to selectively or collectively produce a surface temperature sufficient to desorb some of the adsorbed fluid from the surface. Because the two dissimilar adsorbed fluids **1703, 1704** will desorb at different surface temperatures, the surface temperature is controlled to affect one species of adsorbed fluid

1703, but not the other **1704**, or vice versa. FIG. 25 illustrates, for example, that when the single Peltier heating element **1702** is heated sufficiently, the adsorbed fluid **1704** (shown in FIG. 24) directly over that heating element is removed from the surface **1701**. In addition, FIG. 26 shows that when many or all of the Peltier Effect junctions **1702** are heated to precisely control the temperature of the surface **1701**, one adsorbed fluid species (**1704** in FIG. 23) may be entirely desorbed while the other species **1703** remains on the surface **1701**.

The capturing, or adsorbing, of fluids is illustrated in FIGS. 27 and 28. In FIG. 27, the device **1800** has a surface **1801** provided with Peltier heating elements **1802**. The Peltier elements **1802** are cooled in order to produce a low surface temperature at a specific location on the surface **1801**. As a result, fluids **1803** from the surroundings will preferentially adsorb at that location, as shown in FIG. 28.

One example of a microfluidic manipulator is illustrated in FIGS. 29-33. In FIG. 29, the microfluidic manipulator **1900** has a surface **1901** provided with thermal elements **1902, 1903** arranged in both the X and Y directions for two-dimensional manipulation of adsorbed fluids. The surface area **1901** for adsorption in this example is about one cm^2, but can be made any desired area. The thermal elements **1902, 1903** are 10 μm wide, 500 nm thick, 1cm long, and spaced at a 30 μm pitch. The resistivity of each thermal element is about 100 Ω. The thermal elements **1902, 1903** have pads **1904-1907** at their ends for making external electrical connections. In this example, the pads **1905, 1907** on one side of the thermal elements **1902, 1903** are grounded while the pads **1904, 1906** on the other side of the thermal elements **1902, 1903** are connected with wires **1914** which carry electrical signals that activate the thermal elements **1902, 1903**. For example, the electrical signals required to transport an adsorbed fluid may be a pulse of 20 V, 300 mA amplitude, 10 ms width, and 100 ms period with a repetition rate of 20. Such an electrical signal may be generated with a control system that includes a transistor-transistor logic (TTL) controlled switching system **1910**, a TTL output module **1911**, a programmable DC source **1912**, and a computer **1913**. The DC source **1912** provides the required voltage and current (20 V-300 mA) to the switching system **1910** with electrical

connections **1917**. The DC source may be a power supply, batteries, analog or digital output modules, a pulse generator, etc. In this example, all thermal elements operated simultaneously would receive the same voltage and current. However, each thermal element may also be provided with independent power sources. The TTL output module **1911** selects which thermal elements are to be activated by connecting lines **1916** to the TTL control of each switch **1915**. In addition, the TTL output module **1911** determines the pulse width (10 ms), period (100 ms), and repetition (20). A separate switch **1915** is provided for each thermal element **1902, 1903** that is individually controlled. The switches **1915** may be relays, monolithic ICs, multiplexers, data acquisition (DAC) modules, field programmable gate arrays (FPGAs), application specific integrated circuits (ASICs), etc. The computer **1913** controls the TTL output module **1911** and the programmable DC power supply **1912** through control lines **1918, 1919**.

The construction of the microfluidic manipulator **1900** is illustrated in FIGS. 30 and 31. The surface **1901** is depicted as smooth and flat, although any surface topography can be used. A cross-section along a thermal element **1903** in the Y direction is shown in FIG. 30 and a cross-section along a thermal element **1902** in the X direction is shown in FIG. 31, both figures not to scale. A support **1908** serves as a platform on which the thermal elements **1902 1903** are placed. The support **1908** may be made of insulative or semiconducting materials. Insulative materials include silicon dioxide (SiO_2), silicon nitride (Si_3N_4), silicon carbide (SiC), diamond (C), sapphire, ceramic, silica glass, fused silica, fused quartz and mica. Flexible polymeric insulative materials include silicone rubber, and polyimide. Semiconducting materials include silicon, gallium arsenide, and germanium. The support **1908** may be flexible or rigid and its thickness may vary. For example, a 500-micrometer thick fused quartz wafer may serve as the support **1908**.

In FIGS. 30 and 31, the thermal elements **1903** in the Y direction are located beneath the surface **1901** while their pads **1904, 1905** are exposed to the surface **1901** for electrical connections. The thermal elements **1902** in the X direction are buried about 50nm beneath the thermal elements **1903** in the Y direction while their pads **1906, 1907**

are exposed to the surface **1901** for electrical connections. The types of thermal elements **1902, 1903** include electrical resistive heaters and Peltier Effect junctions. The methods used to fabricate thermal elements **1902, 1903** include conducting thin films and ion implantation. Conducting thin films may be gold, platinum, palladium, aluminum, nickel, copper, and chrome. Compound thin films may be HfB^2, TiWN, $CoSi_2$, $TiSi_2$ or other silicides (molybdenum, tungsten, magnesium). The pads **1904-1907** are made of a conducting material that may be the same as or similar to the thermal elements **1902, 1903**. The thermal elements **1902, 1903** are electrically isolated from each other by means of a surrounding insulative or semiconducting material **1909** similar to the support **1908**. These materials provide electrical isolation for the thermal elements **1902, 1903** as well as thermal isolation for spatially localized thermal gradients and heating.

An example of the operation of the microfluidic manipulator **1900** is shown in FIGS. 32 and 33. In FIG. 32, an adsorbed fluid **1916** on the surface **1901** is located to the right of a thermal element **1903**. The thermal element **1903** is given one or a series of electrical pulses such that a surface tension gradient (not shown) is produced between the adsorbed fluid **1916** and the surface **1901** in the X direction. The surface tension gradient is such that the adsorbed fluid **1916** is transported in the X direction past the adjacent thermal element **1914**, as shown in FIG. 33. Since the transported adsorbed fluid (**1916** in FIG. 33) stops to the right of the adjacent thermal element **1914**, the thermal element **1914** may in turn be activated so that the adsorbed fluid **1916** continues to be transported to the right in the X direction. Only the number of thermal elements available limits the distance transported. If (in FIG. 32) the surface tension gradient is not capable of transporting the adsorbed fluid **1916** beyond the adjacent thermal element **1914,** then the adsorbed fluid will remain between the two thermal elements **1903, 1914**. If the thermal elements **1903, 1914** are Peltier Effect devices, then a steeper thermal gradient is created by heating one thermal element **1903** while cooling the adjacent thermal element **1914**.

While there has been shown and described what are at present considered the preferred embodiments of the invention, it will be obvious to those skilled in the art that

various changes and modifications can be prepared therein without departing from the scope of the invention defined by the appended claims.